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Dust scattering X-ray expanding rings around gamma-ray bursts

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Summary. — Scattering by dust grains in our Galaxy can produce X-ray halos, visible as expanding rings, around GRBs. This has been observed in three GRBs to date, allowing to derive accurate distances for the dust clouds as well as some constraints on the prompt GRB X-ray emission that was not directly observed. We developed a new analysis method to study dust scattering expanding rings and have applied it to all the XMM-Newton and Swift/XRT follow-up observations of GRBs.

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1. – Introduction

Soon after the discovery of celestial X-ray sources it was realized that scattering from interstellar dust grains could lead to the formation of detectable X-ray halos surrounding the source images [1]. The usefulness of this phenomenon to study the properties of the dust was pointed out by several authors, but observations had to await the development of imaging X-ray telescopes. The first dust halos were discovered with the Einstein Observatory around bright galactic sources at the beginning of the eighties [2, 3]. Currently, the modelling of the energy-dependent radial profiles of X-ray halos is a well established tool in the study of the interstellar dust.

Owing to the longer path lengths of scattered compared to unscattered photons, variability in the source can lead to time-dependent changes in the halo radial profile. If the spatial distribution of the dust along the line of sight is known, it is possible to constrain the distance of variable sources by studying their halos [4]. This method was also proposed [5] as a way to distinguish between the galactic and cosmological origin of GRBs, but it could not be applied due to the lack of sensitive imaging detectors.

Only recently dust halos have been detected around three bursts: GRB 031203 [6], GRB 050724 [7] and GRB 050713A [8]. Due to the short duration of the bursts and the relatively small thickness of the dust layers, such halos appear as expanding rings. Since the scattering dust is in our Galaxy, at a distance d_s much smaller than that of the GRB, the ring radius Θ and the time delay $\Delta t = t - t_{GRB}$ are simply related by $\Delta t = (d_s/2c) \Theta^2$. Thus it is possible to accurately measure the dust distance d_s by fitting the time expansion of the ring.

The brightness of the ring depends on the intensity of the GRB emission I_{GRB} and on the scattering optical depth τ : $I_{HALO} = I_{GRB} (1 - e^{-\tau}) \simeq \tau I_{GRB}$. If both I_{HALO} and I_{GRB} are known, as in the case of GRB 050724 [7], some information on the amount of dust and its properties can be derived. In the other two cases observed to date this was not possible and the observations have instead been used to constrain I_{GRB} based on our best guesses on τ . The latter can in fact be estimated from the optical extinction A_V due to the dust layer, although the proper relation between τ and A_V is debated [10, 11] and also the measurement of A_V can be affected by significant uncertainties (in most cases only an estimate of the total A_V along the line of sight is available). These problems are well exemplified by the case of GRB 031203 discussed below.

2. – A new method for the detection of expanding rings in X-ray images

Bright dust scattering rings, like those seen around GRB 031203, can be easily discovered and studied by comparing a sequence of images obtained at different times. However, with this simple method it is difficult to detect fainter halos, as demonstrated by the case of GRB 050713A, whose halo was discovered thanks to a different technique based on “dynamical images” [8]. In a dynamical image all the counts detected by the X-ray telescope are binned according to their squared angular distance from the GRB position (ordinate axis) and their time from the GRB (abscissa axis). Expanding rings are visible as inclined lines whose slope is proportional to $1/d_s$. The 1-2 keV dynamical image for GRB 031203 based on EPIC/pn data is shown in Fig. 1.

The dust distance and the flux in the ring can be measured from the distribution of the quantity $D_i \equiv 2c \Delta t_i / \Theta_i^2$ which can be computed for each count. Only for the scattered X-ray photons this quantity represents the dust distance. Therefore, an expanding ring is visible as a peak centered at d_s in the distribution $n(D)$ of the D_i values. A spatially uniform instrumental background gives a contribution proportional to D^{-2} in the range from $D_{min} = 2c \Delta t_{max} / \Theta_{max}^2$ to $D_{max} = 2c \Delta t_{min} / \Theta_{min}^2$, where Δt_{min} , Δt_{max} , Θ_{min} and Θ_{max} delimit the rectangular region of the dynamical image from which the counts are extracted.

The distributions of D_i for the three GRBs are shown in Fig. 2, where the peaks corresponding to the dust scattering rings are clearly visible. These distributions are well fit with the sum of a power law with slope ~ -2 , representing the background contribution, and Lorentzian curves to model the peaks. The net number of halo counts can then be obtained by integrating the Lorentzians. If enough counts are present in the halos, this procedure can be done in different energy bins to extract the halo spectrum. The results of our fits for the three GRBs are reported in Table I.

We applied this analysis method to all the GRBs observed to date with XMM-Newton and Swift/XRT, without finding any other dust ring. A comparison of the relative success rate of the two satellites (2/15 for XMM-Newton versus 1/150 for Swift) indicates that instruments with large collecting area are required to detect such very faint structures.

3. – GRB 031203

This nearby burst ($z=0.105$) is particularly interesting since it is under-energetic, given its apparently normal hardness, to fit on the correlations followed by most GRBs [12, 13]. Our re-analysis of the INTEGRAL IBIS data with the most recent software and calibrations confirms that the spectrum is well fit by a power-law with photon index 1.69 ± 0.06 (1σ). By fitting with a Band spectrum, a 99% c.l. lower limit of 100 keV can

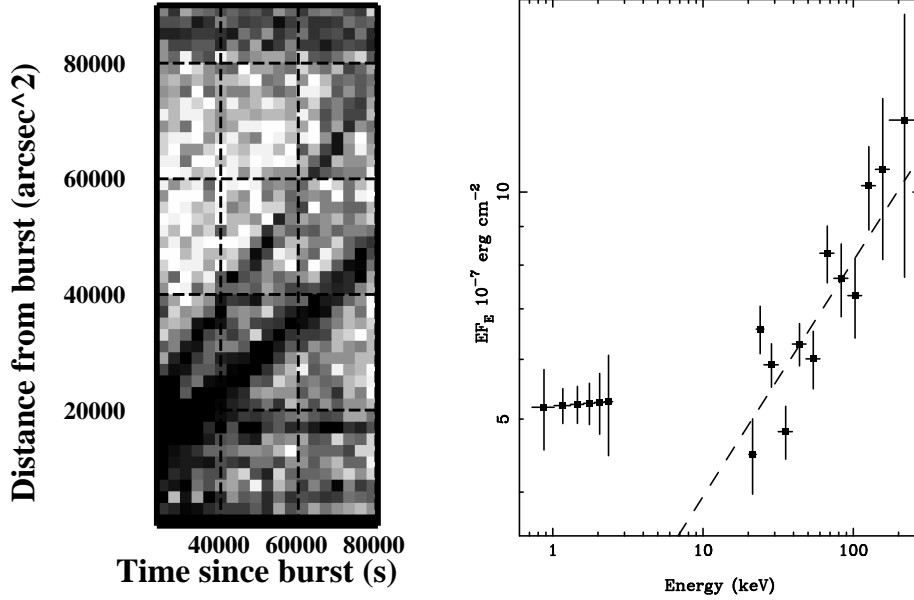


Fig. 1. – Left: Dynamical image of GRB 031203. The inclined lines result from the concentric expanding rings due to two layers of dust at distances of 870 pc (upper line) and 1384 pc. The horizontal lines are X-ray point sources in the field. Right: fluence spectrum of GRB 031203 as measured with IBIS/INTEGRAL above 20 keV and reconstructed from the halo analysis below 3 keV.

be placed on E_{peak} . The 20–200 keV fluence over 40 s is $(1.66 \pm 0.08) \times 10^{-6}$ erg cm $^{-2}$. The fluence in soft X-rays that we inferred from the dust scattering rings is smaller than that derived in [6], but it still exceeds the backward extrapolation of the INTEGRAL spectrum by a significant factor (see Fig.1, right panel). Thus it is likely that the soft

TABLE I. – GRBs with dust scattering halos

	GRB 031203	GRB 050713A	GRB 050724
Galactic coordinates	256, −5	112, +19	350, +15
Galactic N_H (10^{20} cm $^{-2}$)	85	11	15
red-shift	0.1055	–	0.258
GRB discovery	INTEGRAL/IBIS	Swift/BAT	Swift/BAT
Fluence (erg cm $^{-2}$)	$(1.66 \pm 0.08) \times 10^{-6}$ (20–200 keV)	$(9.1 \pm 0.6) \times 10^{-6}$ (15–350 keV)	$(6.3 \pm 1.0) \times 10^{-7}$ (15–350 keV)
Duration (s)	40	70	0.25 (spike) + ~200 (tail)
Halo discovery	XMM-Newton/EPIC	XMM-Newton/EPIC	Swift/XRT
Observed time interval (ks)	23–80	23–46	0.34–2.2, 6.1–8.1
dust layer A_V	2	0.5	1.5
d_s (pc)	870 ± 5 , 1384 ± 9	364^{+6}_{-7}	144 ± 3
I_{HALO} (counts)	840^{+210}_{-180} , 1740^{+270}_{-240}	185^{+120}_{-90}	155^{+167}_{-110}

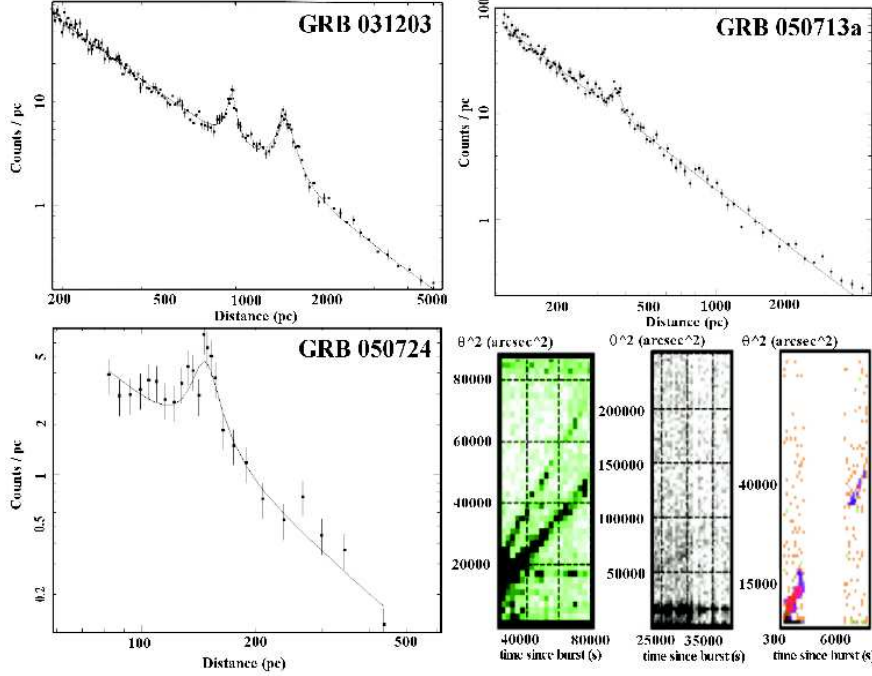


Fig. 2. – Distributions $n(D)$ and best fits with power laws plus Lorentzian curves for the three GRBs with dust scattering expanding rings. The corresponding dynamical images are shown in the bottom right panel.

X-ray emission in GRB 031203 consisted of a delayed component following the hard pulse seen with INTEGRAL, similar to what has been observed in GRB 060218 [14]. In this case GRB 031203 would have a smaller E_{peak} and a higher luminosity, making it in agreement with the “standard” relations.

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